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Review

Beef production and ecosystem services in Canada's prairie provinces: A review

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ABSTRACT

Globally, consumption of bovine meat is projected to increase by 1.2% per annum until 2050, a demand likely met in part by increased Canadian beef production. With this greater production on a finite agricultural land base, there is a need to weigh the contribution of this industry to the Canadian economy against the full range of positive and negative ecological and social impacts of beef production. This review, focussing on the prairie provinces of Alberta, Saskatchewan and Manitoba, which collectively support just over 80% of the Canadian beef herd, examines the social and ecological footprint of the cow-calf, backgrounding, finishing and forage/feed production stages of beef production within an ecosystem services framework. We summarise the literature on how beef production and management practices affect a range of services, including livestock; water supply; water, air and soil quality; climate regulation; zoonotic diseases; cultural services; and biodiversity. Based on 742 peer-reviewed publications, spanning all agricultural stages of beef production, we established a framework for identifying management practices yielding the greatest overall socio-ecological benefits in terms of positive impacts on ecosystem service supply. Further, we identified research gaps and crucial research questions related to the sustainability of beef production systems.

1. Introduction

1.1. Sustainable food production and Canadian beef

In 2015, 37% of the global land area was used for agriculture (World Bank, 2018a). Agricultural systems play a dominant role in feeding the human population and provided 26.5% of global employment in 2017 (World Bank, 2018b). However, agricultural management and deforestation to provide land for farming accounted for 24% of total global greenhouse gas (GHG) emissions in 2014 (FAO, 2017), 70% of freshwater withdrawals worldwide (FAO, 2016), and widespread nitrogen pollution of aquifers (Mateo-Sagasta et al., 2017). A projected rise in the human population to 9.8 billion by 2050 (UN, 2017), coupled with rising per capita food consumption and income, may increase annual global food production by *c.* 60% by 2050 (FAO, 2017).

Global meat production is projected to increase *c.* 200 million tonnes (Mt) by 2050, due to population growth and shifting dietary preferences in developing countries (Alexandratos and Bruinsma, 2012; Hunter et al., 2017). In terms of increased consumption in developing countries, bovine meat is second only to poultry meat, with a projected per annum growth rate of 1.9% from 2005/07 to 2050 (Alexandratos and Bruinsma, 2012). This growing demand will be partially met by an expanded Canadian beef industry, the 11th largest producer and 5th largest exporter of beef globally (CanFax, 2016).

With minimal potential for expanding agricultural land even under climate change scenarios, increases in production will be realized mostly through intensified production and reduced losses throughout the supply chain. In Canada, agricultural land declined from 7.7% to

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6.9% of total land area between 1961 and 2015 (World Bank, 2018a), despite the continual conversion of native grasslands to cropland in the prairie provinces (0.44 million hectares in 2014 - WWF, 2016). Of particular concern is the permanent loss of agricultural land to residential, commercial and industrial development. For example, the province of Alberta lost 5.6% of its agricultural land and converted 23% of pastureland to cropland between 2000 and 2012 (Haarsma et al., 2014).

Global warming may increase food production in Canada due to a northward expansion of suitable growing conditions and a longer grazing season, although weed, pest and disease expansion, combined with increased drought frequency and storm intensity, may limit such gains (Campbell et al., 2014). Moreover, any gains would have to compensate for land lost to development. Therefore, intensified production through increases in carcass weight and enhanced reproductive efficiency appears the most likely way forward (FCC, 2015).

Expected intensification on a shrinking agricultural land base, together with potentially adverse future climatic conditions, warrants an investigation of the full ecological and social impacts of beef production, as recognized globally by the formation of the Global Roundtable on Sustainable Beef (GRSB), and nationally by the Canadian Roundtables on Sustainable Beef (CRSB) and Sustainable Crops (CRSC). Reviews of ecosystem service research exist for pasture-based cattle in Europe (Dumont et al., 2017; Rodríguez-Ortega et al., 2014), and beef cattle on native grasslands in South America (Modernel et al., 2016). Although the environmental footprint of Canadian beef has been widely studied, a holistic investigation of the full range of positive and negative impacts encompassing all stages of beef production (grazing, confined feeding, and forage and feed production) has not yet been conducted (Janzen, 2011).

1.2. An ecosystem services approach to assessing sustainability

A sustainable agricultural system is “one where food is nutritious and accessible for everyone and one where natural resources are managed in a way that maintains ecosystem functions to support current as well as future human needs” (FAO, 2017). This sustainability can be assessed using an ecosystem services framework. Ecosystem services are the outcomes from ecosystems that can lead to benefits valued by people and are produced by the interacting ecological and social structures and processes of the system. Ecosystem services include provisioning services such as water, crop and livestock products; regulating services such as soil, air and water quality regulation; and cultural services such as recreation and tourism. The benefits that flow from these services contribute in varying degrees to the economic, health and social well-being of human beneficiaries (Yahdjian et al., 2015), as they consume, make use of or enjoy these benefits. Changes in human well-being due to changes in the supply of services from the landscape can influence system governance and management, which in turn affect the social and ecological structures and processes that underpin service provision (Reyers et al., 2013) (Fig. 1). For instance, the capacity of the beef system to regulate water quality influences human well-being through effects on the suitability of water for drinking, recreational and other purposes, which motivates the formulation, legislation, and adoption of on-farm best management practices. This framework provides the basis for linking management practices to changes in the total bundle of ecosystem services from beef production, using western Canadian systems as a case-study.

Villamagna et al. (2013) point out that many ecosystem service studies measure environmental quality rather than actual service supply, and recommend instead measuring ecological work, equal to ecological pressures minus environmental quality. For example, sediment filtration performed by a system is equal to cumulative sediment loading in the watershed (ecological pressure) minus ambient sediment concentration (environmental indicator). In this review, direct measurements of regulating service supply were reported where available, e.g., carbon sequestration. However, in many cases, available data related to environmental quality rather than service supply. Nonetheless, environmental quality indicators serve as an effective proxy for regulating services, are readily measured and available, convey meaningful information to decision-makers, and are discussed in this review in the context of their relationships to the services themselves.

The main goal of this review was to investigate: how production practices implemented during the agricultural stages of beef production in the Canadian prairie provinces influence the provision of ecosystem services from this system. More specifically, the objectives of this review were to: (1) synthesize the current knowledge on the provision of ecosystem services from prairie beef production systems, and trade-offs and synergies between different services in response to management practices; and (2) highlight information gaps and priority areas for future research.

2. Methodology

2.1. Beef production system boundaries

Canadian beef production typically consists of a cow-calf stage in which calves remain with the cows on pasture until weaning, and a finishing stage during which weaned calves are fed to slaughter weight in confinement. A backgrounding or growing stage of varying length on pasture and/or in confinement may be included in between the other two stages (Figure 2). In this ‘cradle-to-farm gate’ review, we consider all three stages, with accompanying production of forage and feed crops, and associated social and ecological structures and processes, an approach used in assessments of GHG emissions from Canadian beef production (Beauchemin et al., 2010; Legesse et al., 2016).

Approximately one third (21.1 million hectares, Mha) of agricultural land in Canada supports beef production, including 12.9 Mha of native grassland and 5 Mha of tame/seeded grassland consisting of commercial grass-legume mixtures (CRSB, 2016) (Figure 3). A further 1.8 Mha is used to produce hay (CRSB, 2016) for winter feeding. Annual crops (barley - *Hordeum vulgare*, oats - *Avena sativa,* and corn - *Zea mays*) provide forage, silage and grain, while alfalfa is the most common forage legume grown in western Canada (Sheppard et al., 2015). Across Canada, 1.4 Mha are used to grow feed crops, with the majority (1.1 Mha) used for barley (CRSB, 2016).

In response to rising demand for beef, the total cattle inventory (dairy and beef) rose by 57% nationally and by 160% in the prairie provinces between 1950 and 2015 (Statistics Canada, 2017a). The proportion of the national herd raised in these provinces has also increased over time, from 43% in 1950 to 71% in 2015 (Statistics Canada, 2017a). Canada’s beef cattle are particularly unevenly distributed: more than 80% of the national beef herd is raised in Alberta (AB; 46%), Saskatchewan (SK; 23.8%) and Manitoba (MB; 10.1%) (Statistics Canada, 2017a). Feedlots are also concentrated in southern Alberta (capacity of 1.24 million cattle - CanFax, 2015), co-located with the major barley growing areas.

Climatic conditions and soil type vary across the prairies, with the driest areas in the Mixed grassland ecoregions of the south-west prairies receiving 201-400 mm of precipitation per year (Natural Resources Canada, 2009) and dominated by Brown and Dark Brown Chernozemic soils. Precipitation increases from southwest to northeast, with the Black and Dark Grey soil zones of the Aspen parkland, Peace lowland, Boreal transition and Lake Manitoba plain ecoregions receiving 401-600 mm per year (Natural Resources Canada, 2009). From 1980-2010, mean annual temperatures ranged from -14 to -4 °C in winter (Dec-Jan-Feb; Environment Canada, 2016a) and from 14 to 20 °C in summer (Jun-Jul-Aug; Environment Canada, 2016b).

We considered nine ecosystem services: livestock[1], water supply,

[1] Information on livestock production derives from additional non-peer-reviewed sources

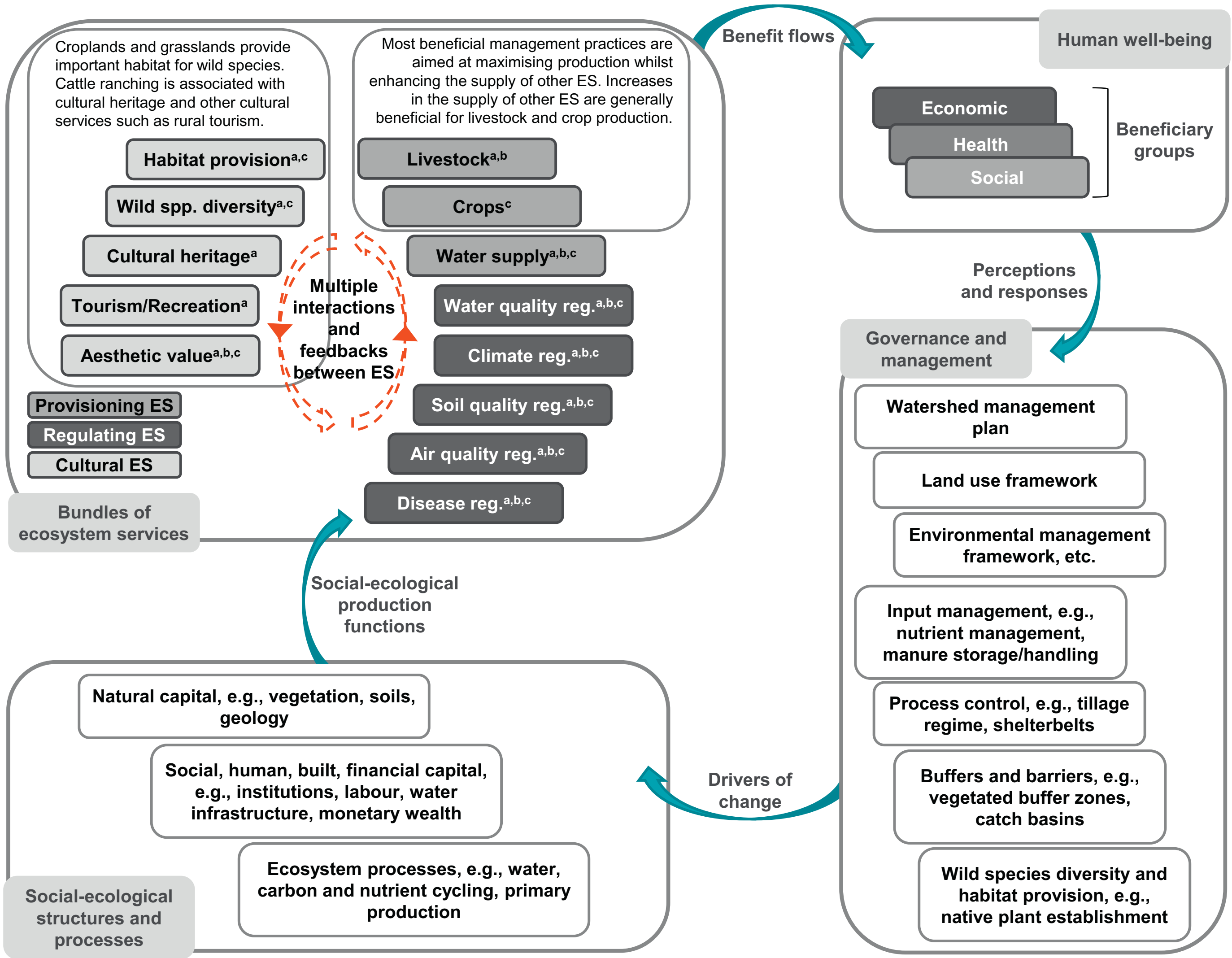

Fig. 1. Conceptual ecosystem service framework for Canadian Prairie beef systems. Superscript letters indicate which stages of beef production are linked to the provision of specific services: [a]Cow-calf and backgrounding on pasture; [b]Backgrounding and finishing in feedlot; [c]Forage and feed production. ES = ecosystem service. Source: modified from Reyers et al. (2013).

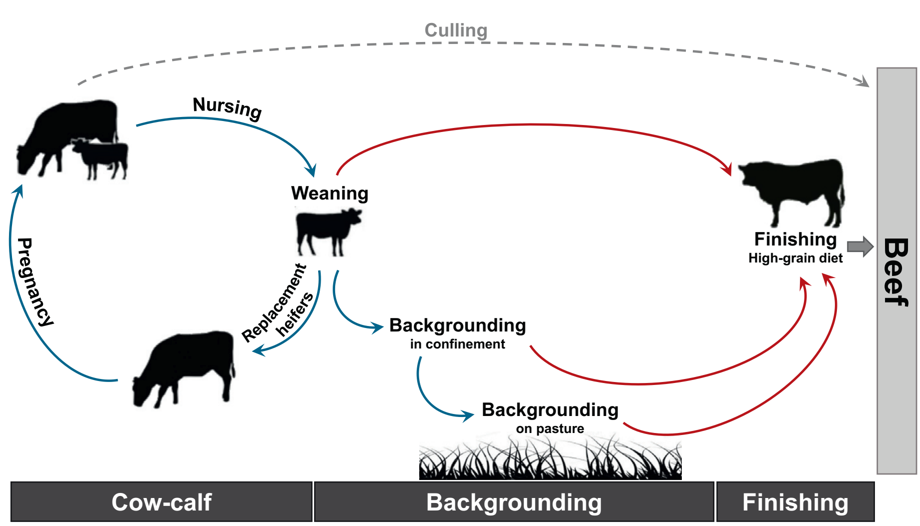

Fig. 2. Overview of beef production in Canada (Source: Legesse et al., 2018). On July 1st, 2016, there were over 9 million beef cattle in the prairie provinces, 64.2% in cow-calf operations, 23.1% in feeder/stocker (backgrounding) operations and 12.7% in feedlots (finishing) (Statistics Canada, 2017a).

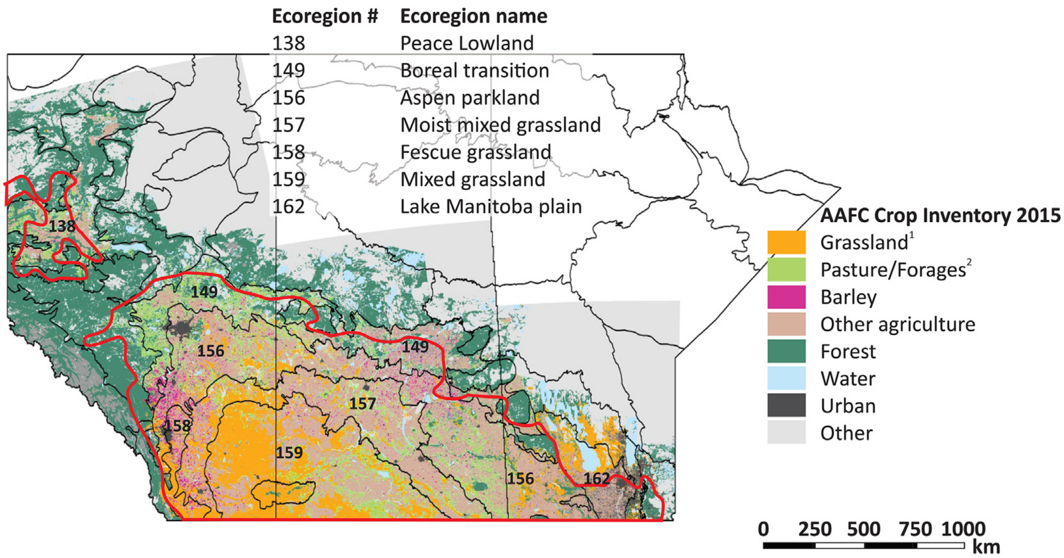

Fig. 3. AAFC Annual Crop Inventory 2015 (AAFC, 2016) for Alberta (left), Saskatchewan (centre) and Manitoba (right). Outlines in black represent: numbered ecoregions. Outlines in red represent: spatial distribution of beef cows (breeding animals) in 2011 (Statistics Canada, 2014a). [1]Predominantly native grasses and other herbaceous vegetation. [2]Tame grasses and other perennial crops such as alfalfa grown alone or as mixtures for hay, pasture or seed.

water, air and soil quality regulation, climate regulation, disease regulation (zoonotic diseases[2]), cultural heritage, and recreation and tourism. The impacts of beef production on wildlife habitat and species diversity are also included, as biodiversity is an ecosystem service and regulates the processes that provide a range of other services (Mace et al., 2012). Management practices that affect the system's social and ecological structures and processes, ecosystem service flows and environmental quality were considered, including beneficial management practices (BMPs; detailed in Appendix A).

2.2. Systematic review

2.2.1. Literature identification and screening

Relevant peer-reviewed studies were identified by searching Web of Science (WoS), Scopus and Google Scholar databases for the Jan 1980-Oct 2016 period (search terms detailed in Appendix B). The terms were searched for in all fields of WoS; in title, keywords and abstract of Scopus; and in titles only of Google Scholar. Search results (total of 37,682 unique records) were imported into EndNote® X7 referencing software (Thomas Reuters, 2013). All screening was carried out by a single reviewer. Studies were initially filtered by title to exclude obviously irrelevant and non-English articles. Remaining articles were screened for relevance based on their abstract, to include only those focussing on the impact of beef production and management practices during the cow-calf, backgrounding, finishing and forage/feed production stages on ecosystem services or on indicators of environmental quality serving as proxies for regulating services. Records for which the full text was not available were also eliminated, leaving 742 records that were then classified based on the primary ecosystem service considered.

2.2.2. Qualitative assessment of ecosystem service impacts

A group qualitative assessment was carried out by the authors based on their expert opinion, bolstered by the literature review. This assessment provides an overview and summary of: (1) the influence of prairie beef production practices on ecosystem service supply; (2) our confidence in the existing data on the influence of beef production on service supply; (3) the responsiveness of individual services to management practices; and (4) the opportunity to improve the supply of different services via further research. For each of the nine ecosystem services and biodiversity and habitat provision, and for each of the four themes outlined above, every stage of production (pasture/cow-calf, feedlot and forage/feed production) was assigned a score via consensus among the authors. The influence of prairie beef production on service supply was scored using a 7-step scale ranging from large positive to large negative. Confidence in the data, responsiveness to management, and opportunity to improve service supply via further research were scored as high, medium or low for each service and stage of production (Appendix C).

3. Results and Discussion

3.1. Classification of relevant records

In the 742 relevant records, the services most commonly examined were soil and water quality, disease, and climate regulation, with relatively few studies on air quality regulation. Information on cultural services such as cultural heritage and tourism and recreation was particularly sparse. The annual number of publications generally increased over time, peaking in 2006 (Figure 4).

3.2. Research findings by ecosystem service

3.2.1. Production of food and non-food goods

Prairie beef production systems are managed with the primary goal of producing livestock that supply numerous market and non-market goods. Foremost among these products is beef, of which Alberta produced 0.76 Mt in 2015 (GoA, 2016), accounting for approximately 58% of total national production (CCA, 2017). Beef and other meat products contribute to human well-being by providing nutrition; for instance, a 75 g portion of cooked sirloin steak trimmed of visible fat provides 21 g protein, 2.6 g saturated fat, 2 mg iron and 13 other essential nutrients (Health Canada, 2008). Other market goods derived from beef cattle include more than 100 human medicines; leather; and products made from the hair (e.g., air filters, brushes), fat (e.g., rubber, oils), blood (e.g., adhesives, dyes and inks), hooves and horns (e.g., plastics, shampoo), organs (e.g., offal, insulin) and bones (e.g., charcoal, glass) (Farm and Food Care Ontario, 2016). The sale of these goods generates income for producers, contributing to their economic well-being; in

[2] Only zoonoses that can be transmitted to humans from beef cattle and that are not classed as "eradicated" in Canada were included (see Appendix B).

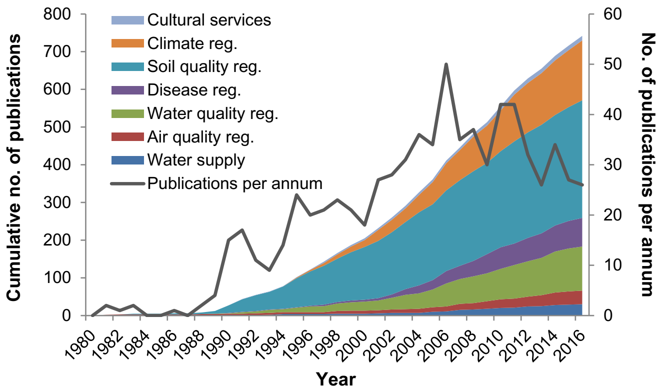

Fig. 4. Cumulative number of relevant publications for each ecosystem service from 1980 to 2016. The total number of publications per annum for all services is indicated by the black line. Cultural services = cultural heritage; recreation and tourism.

2016 cattle contributed 33.9, 9.0 and 9.3% of total farm cash receipts for Alberta, Saskatchewan, and Manitoba, respectively (Statistics Canada, 2017b). Prairie beef cattle also produced *c.* 82.8 Mt of manure in 2016[3], a valuable organic fertilizer that can reduce the need for expensive commercial fertilizers and their associated environmental threats, but also represents an environmental risk and can erode the provision of other services when not managed carefully (Larney and Angers, 2012; Miller et al., 2010a).

The beef industry represents an important source of livelihood for producers and provides numerous market goods to both domestic and international consumers, including skins and fibres for clothing, and the recycling of nutrients from waste, crop residues and fibrous vegetation. The contribution of these products to human economic and health well-being must be viewed within the context of their broader social and environmental footprint via their impacts on ecosystem services.

3.2.2. Water supply

The depletion of water resources has become a concern locally and globally, and beef cattle are under increased public scrutiny due to concerns about water use per unit of beef produced. This has led to intensified effort to estimate water use and to identify and implement water-conserving strategies (Legesse et al., 2017). One report by the Canadian Roundtable for Sustainable Beef estimated that 631 L of water (excluding precipitation) was required to produce a kg of boneless beef, with on-farm (cradle-to-farm gate) production representing about 75% of the total (CRSB, 2016).

Canada is perceived as water-rich due to large reserves of freshwater in lakes, rivers, wetlands and groundwater (Statistics Canada, 2010), but the availability of water varies substantially across the country. Drainage regions in the prairies have freshwater yields of $< 0.1\ m^3/m^2$, while the national average is $0.35\ m^3/m^2$ (Statistics Canada, 2010). The southern prairies are relatively dry, with water availability for beef and forage production impacted by water use by the rapidly expanding human population and associated infrastructure (Percy, 2005). In 2007, 75% of Canada's irrigated land was in the prairies, 60% of it in Alberta which accounts for 75% of water used for irrigation (Rahman et al., 2011; Statistics Canada, 2010, 2013). Of the 12.15 Mha of crops and tame/seeded pastures in Alberta (Statistics Canada, 2017c), 420,940 ha are irrigated (~3.5%), with ~33% of this land area used to grow hay or ensilage (Statistics Canada, 2013).

[3] This figure was estimated using beef cattle numbers on July 1st 2016 (Statistics Canada, 2017a) and daily manure production rates for beef cows, bulls, steers, heifers and calves (Statistics Canada, 2008). It was assumed that cattle numbers remained constant throughout the year, although they actually fluctuate.

About 80% of the surface and ground water used during on-farm beef production is to produce forages and feed crops (Blümmel et al., 2014; Chapagain and Hoekstra, 2003), a use which can positively or negatively affect water flows through abstracting surface or groundwater for irrigation, land cover changes, and changes in land use management (Deutsch et al., 2010). Virtual water embedded within feeds is also imported from other regions of Canada through the transportation of feed crops across provincial borders, especially from Saskatchewan and Manitoba into Alberta (Ramsay and Schmitz, 2002). The efficiency of water use for beef production can be enhanced by improving feed crop yield per unit area; increasing the use of crop by-products and residues; and adopting water conservation management practices and efficient irrigation practices (Legesse et al., 2017). Well-managed rangelands and perennial cover crops can reduce surface runoff and soil erosion and improve water recharge and infiltration (Weber and Cutlac, 2017). Furthermore, beef cattle obtain a large share of their nutrients from marginal lands and rangelands that mainly rely on natural precipitation and are unsuitable for other agricultural activities. However, improper management of beef cattle may damage riparian areas and contaminate surface water from manure (Miller et al., 2011a; Scrimgeour and Kendall, 2002; Statistics Canada, 2014b), decreasing the supply of good quality water for other uses.

As all ecosystem services are connected and maintained by water (Acreman, 1999), managing water efficiently is critical for the sustainability of beef production systems. Under alternative land use and management practices, there are multifaceted interactions and trade-offs among services such as C sequestration and water yield (Kim et al., 2016). Strategies that improve water use may reduce C storage and vice versa (Jackson et al., 2002; Kim et al., 2016). The cultivation of rain-fed grasslands in Argentina and the US increased groundwater recharge and decreased C storage, while woody encroachment onto grassland had the opposite effects (Kim et al., 2016). However synergies can also occur, as practices that increase C storage enhance water regulation. For instance, perennial plants increase infiltration of water into the soil (Lovell and Sullivan, 2006), and shelterbelts trap snow in the winter months, reducing moisture loss due to sublimation and potentially providing direct moisture for the following year's crop or ground and surface water recharge (Kort et al., 2011). Therefore, measures to enhance water use efficiency in beef cattle production need to carefully consider trade-offs between water use and other services, such as C sequestration and GHG emissions.

3.2.3. Water quality regulation

Beef production can influence the amount of good quality water available to human users within the watershed and further downstream. For example, grasslands that support beef production regulate water quality by preventing soil erosion, trapping sediments, recycling nutrients, detoxifying chemicals, replenishing groundwater supplies and controlling surface runoff that transports pollutants to surface water bodies (Heidenreich, 2009; Macleod and Ferrier, 2011). These functions are influenced by soil physical, chemical and biological properties, vegetation presence and type, geology, climate and current and historic management practices (AEP, 2017).

In southern Alberta, increased pathogen concentrations have been detected in water bodies downstream of high cattle densities in pastures and feedlots (Jokinen et al., 2011, 2015; Khan et al., 2014). Natural hormones and veterinary growth promoters (Jeffries et al., 2010) and antimicrobials (Forrest et al., 2011) used in beef production have also been detected. However, sources are not always clear in mixed-use watersheds, as natural hormones can originate from beef cattle or municipal wastewater (Jeffries et al., 2010), nutrients from agricultural or other sources (Burke, 2016), and pathogens from wildlife, humans or livestock (Jokinen et al., 2011; Tambalo et al., 2016).

Some studies found positive correlations between pathogen loads and the presence of beef cattle (Cooke et al., 2002), but others found that feedlot manure (Johnson et al., 2003) or land use by beef cattle

(Little et al., 2003) had no relationship to surface water pathogen concentrations, possibly reflecting BMP adoption by livestock producers. Increases in bacterial and chemical indicators downstream of beef operations can occur in runoff from major precipitation events (Jokinen et al., 2012; Koning et al., 2006), which also promotes the recirculation of sediment-bound contaminants in the water column. Waterborne pathogens tend to be higher in spring and summer (Jokinen et al., 2012; Tambalo et al., 2016), perhaps reflecting more livestock on the land and more frequent manure spreading during these seasons.

On pasture, cattle affect runoff quantity and quality via soil compaction and erosion, reduced vegetation and litter cover, reduced water infiltration and through manure deposition. Higher grazing intensities affect the amount of standing vegetation and litter biomass, and therefore runoff and flows of sediments and other contaminants, although impacts can vary depending on precipitation type. For instance, increasing grazing intensity (increasing frequency of grazing and stocking rate) led to increased bare ground and decreased litter biomass in cattle grazed perennial and annual plots, likely causing an increase in rainfall runoff with increasing grazing intensity in perennials in one of two experimental years (Gill et al., 1998). However, snowmelt runoff decreased with increasing grazing intensity on foothills fescue grasslands due to higher standing vegetation which accumulated snow in lower intensity treatments (Naeth and Chanasyk, 1996). Higher stocking rates can also increase runoff of pathogens such as *Giardia* spp. and *Cryptosporidium* spp. (Mapfumo et al., 2002a). Over-wintering of cattle on pasture with frozen soil can increase ammonium (NH_4-N) and phosphate (PO_4-P) losses from urine and dung in snowmelt runoff (Smith et al., 2011). However, the semi-arid climate of the prairies limits runoff volumes (Chanasyk et al., 2003; Mapfumo et al., 2002a), so that even under high intensity grazing the risk of contaminating surface waters may be low (Gill et al., 1998).

The quantity and contaminant load of runoff from pastures can be reduced with practices such as ungrazed vegetative buffer strips (Miller et al., 2015). Surface water quality can also be maintained by carefully managing riparian zones, which physically control and trap runoff, detoxify nutrients, and stabilise banks and shorelines; trees, furthermore, can reduce water temperature and algal growth in the summer by shading (Fitch et al., 2003; Hilliard and Reedyk, 2014). Cattle congregate in riparian areas for their high quality and palatable forage (Bailey et al., 2010), provision of drinking water and shade (Clark, 1998; Kauffman and Krueger, 1984). In the prairies, 43-51% of surveyed beef farms water cattle at natural water bodies (Sheppard and Bittman, 2011). The risk of water contamination by cattle can be limited by off-stream watering, streambank/riparian fencing and the establishment of stabilized stream crossings (LaForge, 2004; Miller et al., 2010b, 2010c, 2013a).

Feedlot runoff may pose a greater risk to water quality than cattle on pastures due to the concentrated transport of nutrients, bacteria (Miller et al., 2004), and antimicrobials (Aust et al., 2008; Srinivas et al., 2015). These risks can be mitigated by using straw rather than woodchip bedding and more frequent pen cleaning (Miller et al., 2006), retention ponds (Li et al., 2011) and constructed wetlands (Pries and McGarry, 2001; Riemersma, 2001). Feedlots can also promote manure seepage through the feedlot floor, typically compacted bare earth in the prairies, impacting groundwater quality (Maule and Fonstad, 2000), although the formation of a manure-soil interface layer due to compaction can act as a sealant to reduce infiltration on both fine- and coarse-textured soils (Miller et al., 2008).

Feedlot manure and catch basin water can be used to fertilize and irrigate forage and feed crops, but there is a risk of water contamination from nitrate (NO_3-N) (Miller et al., 2010a, 2013b) and Cl (Miller et al., 2011b), which can continue after manure application ceases (Benke et al., 2008, 2013). Applying these nutrients judiciously can minimize nutrient loading without hampering yield (Li et al., 2011). Because of greater surface flow, increased nutrient and bacteria levels occur in high irrigation areas (Gannon et al., 2005) and downstream of irrigation return flow canals (Little et al., 2003). Precipitation can also exacerbate irrigation-driven leaching of manure from croplands (Chang and Entz, 1996), and greater P leaching can occur on coarse- vs. medium-textured soils after applying manure to irrigated land (Olson et al., 2010).

Beef production has the potential to influence water quality both on- and off-farm, but in the prairies low levels of precipitation generally limit surface runoff and leaching, reducing the risk of contaminant transport to water bodies. Implementing BMPs such as feedlot catch basins can prevent negative impacts on water quality while riparian buffer strips and wetlands enhance water purification (see Table 1). Where water quality is reduced by beef production, this indicates that the supply of regulating services from the system is constrained, e.g., water and soil quality regulation, disease regulation. Despite recent progress and some high quality data, further work should distinguish between water contamination from beef cattle and other sources, for example by paired sampling in beef-impacted and non-human-impacted watersheds and the use of DNA-identifying techniques (e.g., Tambalo et al., 2012).

3.2.4. Air quality regulation

Beef production affects air quality through the release of contaminants, causing unpleasant odours and respiratory problems (Bittman et al., 2014; Nimmermark, 2004). These effects can be mitigated through practices that promote the degradation and reduce the dispersion of these contaminants such as the planting of shelterbelts. Manure releases unpleasant odours and land-applied pesticides can become airborne through spray drift, wind-eroded soil, and volatilization from land, water or vegetation, and by being attached to wind-blown sediment (Larney et al., 1999). Ammonia (NH_3) emissions from manure, fertilizer and soil can react with acid gases in the atmosphere to form fine secondary particulates (Bittman et al., 2014). Likewise, overgrazing and cropping activities can increase atmospheric concentrations of fine particulate matter ($PM_{2.5}$) (ECCC, 2016a).

Ammonia volatilization from cattle dung and urine represents a major loss of N, with beef cattle contributing 31% of total Canadian agricultural emissions in 2011 (Sheppard and Bittman, 2016). The highest NH_3 emission rates are associated with cattle manure in feedlots [39% – 72% of N uptake (McGinn et al., 2016; Van Haarlem et al., 2008)], due to high stocking densities (McGinn et al., 2003), high crude protein content of feedlot diets (Van Haarlem et al., 2008) and manure accumulation within pens (McGinn et al., 2007). Downwind deposition of NH_3 from feedlots can lead to N levels that meet or exceed the requirements of crops and should be considered when applying manure and N fertilizer (Hao et al., 2009).

On pasture, N excretion (in urine) and NH_3 emission rates rise with increased forage protein content, which is higher in early- vs. late-season forages, mixed forages with a high legume content, and manured or fertilized forages and pasture (Sheppard and Bittman, 2011; Thiessen Martens and Entz, 2011). In the prairies, pastures and grasslands typically contain < 25% legume and are generally not fertilized (Sheppard et al., 2015), and urine N is readily absorbed by plants, leading to low N volatilization rates (Bittman et al., 2014), especially during winter (Sheppard and Bittman, 2011). Consequently, beef cows emit only 42% of total beef NH_3 emissions as much of their N excretion occurs on pasture, despite constituting 55% of total herd biomass

Table 1
Summary of the influence of the agricultural stages of beef production on ecosystem services in the prairie provinces; our level of confidence in the existing data on the influence of beef production on service supply; the responsiveness of different services to management practices; and the opportunity to improve service supply from these systems via further research.

Ecosystem service[1]	Beef influence on service supply			Confidence in data on service supply			Responsiveness to management			Opportunity to improve			Relevant text section
	P	F	C	P	F	C	P	F	C	P	F	C	
Provisioning services													
Food production	Moderate (positive)	Large (positive)	/	H	H	/	M	M	/	L	L	/	3.2.1
Non-food goods production	Moderate (positive)	Large (positive)	/	H	H	/	M	M	/	L	L	/	3.2.1
Water supply[2]	Slight (negative)	Slight (negative)	Large (negative)	H	H	M	L	L	H	L	L	M	3.2.2
Regulating services													
Water quality regulation	Slight (negative)	Moderate (negative)	Moderate (negative)	M	M	M	H	H	H	M	M	M	3.2.3
Air quality regulation	Moderate (positive)	Moderate (negative)	Slight (negative)	H	H	H	L	L	H	L	M	H	3.2.4
Disease regulation	Slight (negative)	Moderate (negative)	/	H	H	/	H	H	/	M	H	/	3.2.5
Soil quality regulation	Slight (positive)	Moderate (negative)	Moderate (negative)	H	H	H	H	H	H	M	M	M	3.2.6
Climate regulation	Moderate (negative)	Slight (negative)	Slight (negative)	H	H	H	L	L	L	H	H	M	3.2.7
Cultural services													
Cultural heritage	Large (positive)	/	/	L	/	/	L	/	/	M	/	/	3.2.8
Recreation and tourism	Slight (positive)	/	/	L	/	/	H	/	/	H	/	/	3.2.8
Biodiversity and habitat													
Biodiversity	Large (positive)	Large (negative)	Slight (negative)	M	H	M	H	L	M	H	L	H	3.2.9
Habitat maintenance	Large (positive)	Large (negative)	Slight (negative)	H	H	H	H	L	M	H	L	H	3.2.9

Legend

Beef influence
Positive: Large; Moderate; Slight
No change
Negative: Slight; Moderate; Large
/ Not relevant

Confidence in data/ Resp. to management/ Opportunity to improve
L Low
M Medium
H High

P = pasture (cow-calf); F = feedlot; C = cropland (forage/feed production incl. tame pasture). [1]Within each ecosystem service there are multiple indicators of service supply, which can be differently influenced by management actions – see relevant sections in text and Table D.1. [2]Water supply refers to blue water (surface and ground water) consumption. Definition of scores is included in Appendix C.

(Sheppard and Bittman, 2012). The exception is pasture areas where cattle congregate, as higher N excretion/accumulation combined with soil compaction and lower infiltration rates increase NH_3 emissions (Sheppard and Bittman, 2011). More even dispersion of cattle throughout the pasture and ensuring that the crude protein content of the diet does not exceed animal requirements can reduce emissions.

Ammonia emissions from feedlot manure occur from its production to land application. Across Canada, NH_3 emissions from confined housing, storage and land-spreading were an estimated 60.1, 7.5 and 32.4% respectively of total emissions from feedlot manure (Sheppard and Bittman, 2013). In western Canada, high NH_3 emissions from manure excreted in feedlots leads to lower emissions from stored manure, as there is little N remaining to volatilize, leach or runoff during storage (Sheppard and Bittman, 2012). Ammonia volatilization rates following land-spreading vary depending on manure storage and handling prior to application. McGinn and Sommer (2007) reported that following application to cropland, stockpiled and compost manure lost 27 and 96% less NH_3 than fresh pen manure, reflecting their higher pre-spreading loss rates. Post-application practices also affect NH_3 losses; for instance, immediate post-application losses from manure can be reduced 21-52% by irrigating and 76-85% by tilling shortly after application (McGinn and Sommer, 2007). However, in western Canada, 61% of beef farms spread manure onto tilled (arable) land, 25% onto perennial cropland, and 14% onto reduced till land, thus 39% of farms cannot incorporate manure into the soil (Sheppard and Bittman, 2012). Therefore, the full impacts of beef cattle manure on NH_3 emissions need to consider total losses from production to land-spreading. Land-applied commercial fertilizers are a further significant NH_3 source, accounting for 35% of national agricultural emissions in 2011 (Sheppard and Bittman, 2016). Perennial forages and pasture in the prairies receive little fertilizer N, and in western Canada emission factors are lower than in the east due partly to the higher use of anhydrous NH_3 and the dominance of banding of granular fertilizers (Sheppard et al., 2010).

Odours, associated primarily with areas of intensive beef production in central and southern Alberta and southern Manitoba (Bittman et al., 2014), are due to emissions from decomposing manure, including NH_3, hydrogen sulfide (H_2S), and volatile organic compounds such as phenols, indoles and volatile fatty acids (VFAs). VFA emissions from beef feedlots are positively correlated with stocking density, but concentrations decline with distance from the feedlot (McGinn et al., 2003). Winter grazing of cattle can decrease NH_3, $PM_{2.5}$ and odour emissions compared with feedlots (Sheppard and Bittman, 2012).

Linking $PM_{2.5}$ emissions and pesticide volatilization to Canadian beef production systems is difficult, as both originate from crops used for livestock feed and human food. Overall, the agriculture sector (livestock, crop production and fertilizer) contributed 20% of national $PM_{2.5}$ emissions in 2014 (ECCC, 2016a). However, prairie farmland saw a decline in total suspended particulates of between 52 and 68% from 1981 to 2011, due to the adoption of no-till cropping systems and a reduction in the use of summer fallow (Pattey et al., 2016). Current-use herbicides applied to agricultural lands in beef producing areas of the prairies have also been detected in air samples from these regions. For example, herbicides widely applied to barley were detected at all sampling sites in the prairie agricultural zone, including MCPA ((4-chloro-2-methylphenoxy)acetic acid) and bromoxynil in Manitoba (Messing et al., 2014a, 2014b) and MCPA, bromoxynil and 2,4-D across the three prairie provinces (Messing et al., 2014b).

Overall, data quality is high, including direct measurements of pollutant emissions from beef operations. The main air quality concerns arise from feedlots due to high cattle densities, high dietary crude protein content, and accumulation of manure, and from croplands amended with manure or fertilizer (see Table 1). Gaseous emissions from the cropping stage can be largely mitigated by practices such as balancing nutrient applications with crop demands and incorporating amendments immediately following application. NH_3 emissions from feedlot manure can be reduced to some extent by increasing the amount of time cattle spend on pasture and balancing animal nutrient requirements with feed protein content. Overall air quality can be improved by planting trees in shelterbelts and forested buffers to reduce soil erosion and trap gaseous and particulate emissions (Davies et al., 2011; Kulshreshtha and Kort, 2009).

3.2.5. Disease regulation

Beef cattle can serve as reservoirs of zoonotic diseases and can transfer potential pathogens via several pathways: (1) contact with infected animals or carcasses; (2) consumption of infected or contaminated meat; and (3) bathing in or consuming water contaminated with waterborne pathogens that originated from cattle manure.

Shiga toxin-producing *E. coli* (STEC) causes enterohemorrhagic diarrhea and kidney failure in humans and has been found in feedlot cattle faeces and the feedlot environment (water troughs, lagoons or dugouts, soils) in southern Alberta and Saskatchewan (*E. coli* O157 and non-O157). Studies have reported faecal prevalence rates of 0-79% for *E. coli* O157 (Stanford et al., 2016; Van Donkersgoed et al., 2009; Vidovic and Korber, 2006) and 7-94% for the other 'top six' STEC serogroups (Stanford et al., 2016), with higher prevalence generally reported during spring/summer than fall/winter (Ekong et al., 2015; Stanford et al., 2016; Van Donkersgoed et al., 2009).

Animal age (Van Donkersgoed et al., 1999) and cattle density (Vidovic and Korber, 2006) also affect *E. coli* shedding, and calving appears to increase overall *E. coli* presence (Gannon et al., 2002). Control measures include endemic bacteriophages, which have been shown to reduce *E. coli* O157:H7 in feedlot cattle (Niu et al., 2009a, 2009b), and composting which can reduce the number of *E. coli* (Larney et al., 2003), *Cryptosporidium* oocysts and *Giardia* cysts (Van Herk et al., 2004) and *Bacillus anthracis* (anthrax) spores in beef cattle manure (Xu et al., 2016). The prevalence of *E. coli* O157 in pastured cattle is low with one study finding a rate of only 1.4% (Vidovic and Korber, 2006).

Salmonella is the second-most prevalent enteric pathogen in Canada (GoC, 2007), although prevalence in feedlot manure, beef carcasses, environmental samples and ground beef is low (1-3%) (Sorensen et al., 2002; Van Donkersgoed et al., 2009). *Salmonella* was recovered from 10% of cow-calf manure samples tested across Canada from 2005 to 2010 (Parmley et al., 2013), but was not detected in faecal samples from Alberta cow-calf herds (Sorensen et al., 2002).

Campylobacter jejuni was detected in 76-90% of Alberta feedlot manure samples (Inglis et al., 2003, 2004; Van Donkersgoed et al., 2009) and 52% of feedlot catch basin water samples in the spring (Van Donkersgoed et al., 2009). *Clostridium difficile* is occasionally isolated from cattle on pastures and in feedlots (Costa et al., 2012), and *Giardia* cysts and *Cryptosporidium* oocysts have been found in backgrounding and finishing cattle (Gow and Waldner, 2006; Ralston et al., 2003). Anthrax outbreaks were reported in Saskatchewan cattle when flooding events were followed by hot, dry summers (Epp et al., 2010a, 2010b; Himsworth and Argue, 2008; Parkinson et al., 2003), and on short-grass pastures with high stocking densities (Epp et al., 2010b; Parkinson et al., 2003). However, human anthrax cases related to animal outbreaks are rare (CFIA, 2013), with only 25 reported cases in Canada since 1931 (GoM, 2015).

Linkages have been established between enterohemorrhagic disease in humans and the presence of *E. coli* and high cattle densities in Alberta (Bifolchi et al., 2014; Pearl et al., 2006). Salmonellosis has also been associated with *Salmonella* Typhimurium and human contact with cattle in Alberta and Saskatchewan (Doré et al., 2004). In Alberta, Q fever has also been identified in humans that work or visit livestock operations (Snedeker and Sikora, 2014). Pathogen spread within the herd and the risk of transmission to humans can be minimised, however, by using well water or denying cattle direct access to dugouts or streams by pumping water into a watering trough. Such practices have been shown to reduce the transmission of *Giardia* and *Cryptosporidium* within the herd (Heitman et al., 2002).

In western Canada, antimicrobials are routinely administered prophylactically to feedlot cattle both through injection and in the feed. Antimicrobials are also used to specifically treat individual animals that exhibit clinical symptoms of disease (Health Canada, 2002). Frequent antimicrobial use (AMU) can lead to antimicrobial resistance (AMR) in bacteria, with potential implications for human health. In 2014, *c.* 82% of antimicrobials used in human medicine were distributed and/or sold for use in food-producing animals in Canada (PHAC, 2016). *E. coli* resistant to antimicrobials have been found in beef cattle (Gow et al., 2008a, 2008b; Stanford et al., 2012), but generally not (yet) to antimicrobials critically important for human health (Aslam et al., 2010; Benedict et al., 2015). Furthermore, AMR *Campylobacter* spp. (Inglis et al., 2006) and *Salmonella* (Rao et al., 2010) were observed in feedlot cattle. Thus far, antimicrobial resistance rates in humans have generally remained stable (PHAC, 2016).

Disease regulation in beef systems and the wider environment is influenced by biotic factors such as pathogens and their hosts, and abiotic factors such as climate, agricultural land use and disease management. The threat to humans arises mainly from waterborne pathogens, highlighting the importance of practices that enhance services controlling the quantity of pathogens in water. Available data measure the occurrence and prevalence of bovine zoonoses in the beef herd and surrounding environment, rather than the degree of disease regulation within the production system. These data indicate potential impacts of beef production on disease dynamics, but further investigation is required to assess what elements of the system regulate these dynamics, how they do this, and how they are influenced by various management practices.

3.2.6. Soil quality regulation

Soil erosion on agricultural land reduces soil quality by depleting nutrients and organic matter, adversely affecting soil productivity (Li et al., 2008). Erosion also reduces air quality as PM and particle-bound contaminants are released to the atmosphere, and water quality is compromised by soil particles and associated contaminants. Cultivated prairie soils are often vulnerable to erosion due to insufficient crop residue or snow cover (McConkey et al., 2012), especially in undulating terrain, which increases water and tillage erosion risk (Li et al., 2007a, 2007b). On more level terrain and on bare soils (due to tillage or fallow), wind erosion is of greater concern.

Climate and landscape conditions determine how effectively management practices can negate erosion risk. On pasture, stocking density can affect erosion via soil compaction and vegetation and litter removal, leading to reduced water infiltration, increasing surface runoff and soil losses. For instance, Gill et al. (1998) and Chanasyk et al. (2003) reported increases in bare soil and decreases in standing vegetation and litter biomass with increasing grazing intensity in Alberta, although soil losses remained well below the maximum tolerable limit of 6 t ha^{-1} yr^{-1} (Gill et al., 1998). However, overgrazing can alter the soil profile, by reducing the thickness of the Ah horizon, both by compaction and by increased soil removal through erosion (Dormaar and Willms, 1998). Perennial vegetation cover and the deposition of cattle dung on pasture can help mitigate erosion (Lobb et al., 2016). The dominance of pasture and perennial forages in western Canadian beef systems and the widespread reduction in stocking rates over the last 80-90 years have improved soil condition following severe deterioration during the Dust Bowl of the 1930s (Wang et al., 2014).

Water erosion in croplands is driven by the timing and form of precipitation, with spring snowmelt representing 85% of annual runoff on the prairies (Nicholaichuk, 1967), generally causing the highest annual soil loss from fallow and tilled fields in semi-arid regions (McConkey et al., 1997). Total water and tillage erosion have resulted in average soil losses of 12.1 $t\ ha^{-1}\ yr^{-1}$ in conventionally tilled Manitoba soils (Li et al., 2007b), and wind-driven losses exceeding 11 $t\ ha^{-1}\ yr^{-1}$ were reported on 57% of sites under tillage-fallow in southern Saskatchewan (Sutherland et al., 1991). On average, since 1981, erosion in prairie soils has declined to $< 6\ t\ ha^{-1}\ yr^{-1}$ due to the adoption of conservation tillage and reduced summer fallowing (Lobb et al., 2016). Winter cover crops, strip cropping, and windbreaks can further reduce soil erosion risk (Pattey et al., 2016). Perennial forages in crop rotations also have more extensive root systems than annual plant communities (DuPont et al., 2010), providing greater erosion control.

The addition of organic matter and nutrients in animal excreta can positively influence soil physical, chemical and biological parameters. In low input pastures, ~87% of ingested N and 90% of ingested P are returned to the soil in faeces and urine (Dahlin et al., 2005). At higher stocking densities, these returns are higher per unit of land, increasing soil NO_3-N levels (Baron et al., 2001). Pasture species composition can also influence soil quality, as roots of perennial grasses had 3.7 times the C and 3.3 times the N as roots of annual grasses (Mapfumo et al., 2002b). Soil NO_3-N and mineral N concentrations were also higher under perennial vs. annual forages (Baron et al., 2001), and mineral N, total C, N and organic C were higher under legume-grass vs. pure-grass pastures (Chen et al., 2001). Winter grazing of beef cattle on cropped land through bale, swath, and straw-chaff grazing leads to significantly increased soil moisture, organic matter and nutrients (Omokanye, 2013). This practice can potentially increase crop/pasture yields in the following year (Jungnitsch et al., 2011). Dung deposition on pasture also promotes populations of dung-dwelling organisms, which break down and return nutrients to the soil. Rotational grazing coupled with sustainable stocking densities and minimizing congregation sites can prevent the localised buildup of nutrients and pathogens in pastures.

Feedlot manure can impact soil quality due to the lateral and vertical transport of nutrients, trace elements, pathogens and pharmaceuticals present in accumulated manure. The transport and accumulation of contaminants beneath the feedlot is usually low in the prairies due to the semi-arid conditions (Godlinski et al., 2011), although nutrient buildup in surrounding soils can occur due to feedlot runoff (Cordeiro et al., 2011) or excessive application of manure. The export of feedlot manure to croplands reduces the risk of air, soil and water contamination from feedlots (Larney and Hao, 2007), and improves soil quality by increasing soil organic matter, soil moisture, and N, P and trace element concentrations and by reducing soil erosion (Larney and Angers, 2012; Larney and Hao, 2007). Combined, these factors can increase crop yields while replacing expensive and energy-intensive commercial fertilizers, which do not directly add organic matter to the soil. Manure also contributes to soil microbial activity which plays a crucial role in nutrient cycling (Lupwayi et al., 2014). In low pH soils (pH 6.5 or less), cattle manure can reduce acidity and increase crop yields (Whalen et al., 2000, 2002).

Although feedlot manure is a valuable organic fertilizer, its long-term application in excess of crop requirements can result in the accumulation of nutrients, soluble salts and trace elements, damaging soil and water quality (Miller et al., 2010a). Applying composted manure increases soil moisture retention and saturated hydraulic conductivity, but this can increase the soil profile mobility of residual soluble salts, total S, metals (Al, Fe) and trace elements (Miller et al., 2013c, 2013d). Composting of manure, practiced by approximately 20% of western Canadian beef producers (Francis Larney, AAFC, pers. comm.)[4], can also significantly reduce levels of antimicrobial residues (Sura et al., 2014).

The impacts of beef production on soil quality have been well-documented via direct measurements of soil erosion and soil nutrient and contaminant concentrations under various farm practices. Beef production on the prairies can effectively reduce soil erosion as it delivers economic benefits from grazing lands, reducing the likelihood of their cultivation, and justifies the use of perennial forages in croplands, making these lands less prone to erosion under sustainable grazing regimes. The deposition of dung and urine on pasture and the application of feedlot manure on agricultural soils can improve biological, chemical and physical soil properties, although manure application must consider the quality of the manure itself, crop nutrient requirements, and soil nutrient content, to avoid the accumulation of nutrients, pathogens and other potential contaminants of freshwater resources.

3.2.7. Climate regulation

Beef systems impact climate by emitting carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), but the grassland pastures that support grazing cattle represent a significant C stock, with the potential for additional C sequestration under appropriate practices. Emissions of CO_2 arise from on-farm energy use and off-farm fertilizer and pesticide production. Methane is produced via enteric fermentation in cattle and the anaerobic decay of manure. Nitrous oxide is emitted directly from transformations of fertilizers, crop residues, manure, and soil organic matter, and indirectly from N lost via leaching, runoff and volatilization (Worth et al., 2016). From 1990 to 2013, Canadian agricultural CH_4 emissions rose by 9% and N_2O emissions by 35%, mostly from higher N fertilizer use (Environment Canada, 2015). Canada is committed to reducing overall GHG emissions by 30% below 2005 levels by 2030 (ECCC, 2016b), therefore assessing GHG fluxes from beef production is crucial.

When accounting for all GHG sources (enteric CH_4 from grazing cattle, grassland CO_2 fluxes and N_2O losses from urine patches), grasslands can become a net source of GHGs (McGinn et al., 2014). Feedlot cattle produce lower amounts of enteric CH_4 than grazing cattle due to the shorter retention of grain-rich feedlot diets in the rumen (Harper et al., 1999). Consequently, Beauchemin et al. (2010, 2011) found that the cow-calf sector accounts for *c.* 80% of total GHG emissions from a typical western Canadian beef production system that considered all GHG emissions from cows, bulls and their progeny, the cropland that supplied forage/feed, on-farm energy use and the manufacture and application of inputs (fertilizer, herbicides). Diet composition generally affects multiple GHG emission sources; for instance, using corn dried distillers' grain in feedlot diets in place of barley grain decreases enteric CH_4 emissions, but the use of both corn and wheat distiller's grains increases N excretion and the resulting N_2O formed leads to a net increase in total GHG emissions (Hünerberg et al., 2014). However, winter swath-grazing of beef cattle on corn and triticale can lower total GHG emissions relative to a conventional drylot system as emissions from manure are reduced (Alemu et al., 2016).

Legesse et al. (2016) used Holos, an empirical whole-farm system model, to estimate that from 1981 to 2011, CH_4, N_2O and CO_2 emissions per kg of beef produced declined by 14, 15 and 12% respectively,

[4] Sheppard and Bittman (2012) reported that 20-30% of surveyed beef operations in western Canada composted manure, although as the definition of composting was not specified in the questionnaire, the answers reflect the understanding of the term by the farmers.

equivalent to a decline of 14% in GHG intensity (from 14 to 12 kg CO_2 eq. kg live wt^{-1} from 1981 to 2011). For comparison, these authors recalculated previous GHG estimates from the Canadian beef industry by Vergé et al. (2008) and Beauchemin et al. (2010) using the latest global warming potential coefficients from Myhre et al. (2013). This resulted in estimates of 18 and 11.7 kg CO_2 eq. kg live wt^{-1} for 1981 and 2001 respectively from Vergé et al. (2008), and 14.6 kg CO_2 eq. kg live wt^{-1} from Beauchemin et al. (2010). From the latter study, the largest sources of GHG emissions were enteric CH_4 (63% of all emissions) and N_2O from soil and manure (27%). Differences in estimates could be due to differences in the systems under examination and in GHG estimation methodology. The Beauchemin et al. (2010) estimate was based on a simulated southern Alberta beef system, while Vergé et al. (2008) and Legesse et al. (2016) used a nationwide, industry-level approach. Variation between the two latter studies could be attributed to several factors. Vergé et al. (2008) estimated enteric CH_4 emissions based on a single emission factor, and included CO_2 emissions associated with farm machinery manufacture in their calculations. Legesse et al. (2016) estimated enteric CH_4 emissions based on IPCC (2006) and relevant Canadian studies (Little et al., 2013), and did not include CO_2 emissions from farm machinery manufacture (Legesse et al., 2016).

Cropland GHG emissions depend on manure and fertilizer use, tillage, fallow and irrigation regimes. Applying manure to southern Alberta soils increased N_2O emissions, with slightly higher emission rates from irrigated vs. non-irrigated soils (Hao, 2015). Climatic conditions also affect emissions; for example, N_2O emissions per hectare in semi-arid western Canada are lower than those in the more humid east (Worth et al., 2016). Prairie agroforestry practices (e.g., shelterbelts, riparian buffers) regulate the climate by acting as a long-term C sink and providing input to the soil C pool via litterfall (Oelbermann et al., 2004). They also reduce soil erosion, improve air and water quality, provide aesthetic value, and offer wildlife habitat (Kulshreshtha and Kort, 2009; Kulshreshtha et al., 2011). When all GHGs are considered, forested soils have lower emissions than soils in adjacent non-treed areas, due to greater CH_4 uptake, lower N_2O emissions and enhanced C storage (Amadi et al., 2016; Baah-Acheamfour et al., 2016).

Net CO_2 emissions from agriculture declined from 1990 to 2012 as agricultural soils became a net C sink due to an increase in no-tillage practices and a decrease in summer fallow (Environment Canada, 2015). Based on findings from long-term experiments and field trials, soil organic carbon (SOC) in arable lands can be increased by adopting conservation tillage, avoiding summer fallow, restoring perennial or native vegetation, and increasing yields through nutrient amendment (Hutchinson et al., 2007; Janzen et al., 1998; Pennock, 2005; VandenBygaart et al., 2003, 2010, 2011; Yang et al., 2013). For instance, shifting to conservation tillage has been estimated to increase SOC by 0.14 Mg C ha^{-1} yr^{-1} in the top 15 cm of western Canadian soils (VandenBygaart et al., 2010). However, these gains are vulnerable to loss with a reversion to previous practices (Shahidi et al., 2014). The inclusion of perennial legume and grass forages in crop rotations can also increase soil C content due to the greater biomass and distribution of roots in perennial vs. annual plant communities, suggesting the former provides a relatively greater contribution of organic C to the soil (DuPont et al., 2010). The inclusion of legumes in crop rotations also affects GHG emissions due to biological N fixation, reducing energy-related emissions and the need for commercial N fertilizers, limiting NO_3-N leaching and N_2O losses (Asgedom and Kebreab, 2011). Grazing cattle on annual green manure or cover crops also provides direct inputs of organic matter and plant-available nutrients to the soil, benefiting soil quality and increasing soil C content, and reduces GHG emissions from fossil fuels as crops are terminated by grazing rather than by tillage operations (Thiessen Martens and Entz, 2011).

On pasture, grazing can increase net primary productivity and net soil C gains can occur under a range of grazing practices (Wang et al., 2014), but thus far no definitive conclusion has been reached regarding optimal stocking rates for grassland C sequestration and storage. Wang et al. (2014), in a review of pasture management studies on Canadian grasslands, reported that soil C increased under both light and heavy grazing, although Franzluebbers and Stuedemann (2009) reported that in the southeastern US, low pressure grazing of pasture by cattle led to significantly greater levels of SOC accumulation in soil (0-90 cm) than in ungrazed or heavily grazed pastures. Although net soil C sequestration can take place even under high grazing intensities, in southern Alberta estimated C contributions from litter and roots decreased from 1,810 to 1,550 and 1,210 kg C ha^{-1} under light, medium and heavy grazing intensities, respectively (Mapfumo et al., 2002b). In the same study, perennial grasses contributed 2,608 kg C ha^{-1}, compared with 962 kg C ha^{-1} for annual grasses. The adoption of sustainable pasture management practices including reduced stocking rates since the 1950s has contributed to the sequestration of C in prairie grassland soils over the last 70 to 80 years. This has led to the recovery of C lost during the period of grassland degradation in the first half of the 20^{th} century, and the offsetting of an estimated 5.84 Mg C ha^{-1} CO_2 eq. of anthropogenic CO_2 emissions (Wang et al., 2016). However, grassland C dynamics also depend on climate; for example, in the Great Plains, grasslands may be a net C sink in wet years and a net source in others (Petrie et al., 2016).

Beef production systems in the Canadian Prairies are net producers of GHGs, although overall emission intensities have decreased over time. However, trade-offs exist between different stages of the production process, and decisions to reduce GHG emissions must be based on net emissions that consider all stages of the production process and alternative management practices (Asgedom and Kebreab, 2011). For instance, although sustainable pasture management can increase soil C sequestration, grazing cattle are responsible for most of the GHG emissions attributable to the agricultural stages of beef production. Thus, the greatest potential for further reducing net emissions relate to reducing CH_4 emissions from grazing cattle (see Table 1), perhaps by enhancing the diet quality of these animals. Certain management practices including conservation tillage, perennial forages in crop rotations, cover crop grazing, tree planting, and reduced stocking rates can act as climate change mitigation measures, via increased soil C sequestration and avoided emissions related to fossil fuel energy use and N fertilizer application. However, gains from adopting BMPs are lower in soils with higher initial SOC levels, and soils have a finite capacity to sequester SOC.

3.2.8. Cultural services

The provision of cultural services from prairie beef production systems derives primarily from rangelands and ranching activities, and is strongly associated with the cultural heritage of the region and central to rural tourism activities. Cultural heritage refers to physical artefacts and intangible attributes that groups or societies inherit from past generations and which they maintain for the benefit of future generations (UNESCO, 2017). In the context of prairie beef production, cultural heritage relates to cattle ranching activities, which are defining features of provincial identity and central to the agricultural, culinary and historical landscape. The slogan "If it ain't Alberta, it ain't beef" and the term "Alberta beef", popularised in the late 1980s by the Alberta Beef Producers and central to their marketing campaign, were designed to reflect a "traditional and "authentic" mode of cattle production" centered around the cowboy; this campaign succeeded in incorporating Alberta beef into the cultural imaginary, making it an authentic feature of the province's heritage (Blue, 2008).

Irshad (2010) outlines three major types of rural tourism: (1) cultural heritage tourism - leisure travel that serves primarily to experience places and activities that represent the past; (2) nature-based tourism or ecotourism - the visitation of natural areas for the purpose of enjoying the scenery; and (3) agritourism - the act of visiting a working farm or any agricultural, horticultural or agribusiness operation for the purpose of enjoyment, education or active involvement in farm activities. A prominent cultural heritage tourism event in the region is the Calgary Stampede, begun in 1912, which attracts over a million visitors each summer to its rodeo and other agricultural activities (Calgary Stampede, 2017). Nature-based tourism activities on prairie rangelands include recreational opportunities for hikers, photographers, hunters and other outdoor enthusiasts (Bailey et al., 2010).

The agritourism sector has expanded in recent decades, as evident in increasing farm-based tourism and recreation activities in Saskatchewan (Fennell and Weaver, 1997; Weaver, 1997; Weaver and Fennell, 1997), Manitoba (Glenn and Rounds, 1997), and Alberta (Hanson, 2013), showing that many farmers augment their income through farm-based tourism and recreation activities. The trend has been further amplified by an increase in consumer discretionary incomes, vacation time, and environmental awareness, and by people's nostalgia for "a simpler time" (Ainley and Smale, 2010). Most agritourism farms and other farm-based recreational activities occur in the prairie ecoregions, with 80% of Saskatchewan's vacation farms located in the prairie areas of this province (Fennell and Weaver, 1997). Irrigation reservoirs in the prairies, meant to provide water for crops, also supply a range of recreational services such as fishing, boating, wildlife watching and ice-fishing (AF, 2000).

Canadian Prairie rangelands and cattle ranches underpin concepts of cultural heritage in these provinces and can supply a range of rural tourism activities, but available information is sparse and many of the relevant records are outdated (see Koster, 2010). The rural tourism sector not only provides benefits to visitors and tourists, but also to ranching communities via the diversification of income for producers, increased employment, community pride and cultural heritage, while promoting conservation and environmental enhancements (Irshad, 2010). These benefits can increase the economic, environmental and social sustainability and resilience of the system.

3.2.9. Maintenance of biodiversity and support of species habitats

Grassland habitats are subject to natural disturbances and drivers such as fire, drought, and grazing (Askins et al., 2007; Bork et al., 2012). Historically, grazing bison created a heterogeneous habitat, thus increasing species diversity of the landscape. These patterns were sustained to some extent after European settlement by the intensification of grazing agriculture which prevents woody plant and scrub encroachment while maintaining the habitats of the shortgrass prairie (Watkinson and Ormerod, 2001). Grazing management practices and stocking density can induce different responses in native taxa, complicating impact assessments of grazing on biodiversity (Hart, 2001; Steinfeld et al., 2010). In general, moderate grazing promotes plant species richness by opening new niches and increasing the spatial heterogeneity of habitats (Milchunas et al., 1998).

The impacts of grazing cattle on wildlife can be direct, such as interference competition due to the physical presence of livestock on shared rangelands, or indirect through changes they create in vegetation, with stocking rates or grazing intensity perhaps the most important factors governing changes in biodiversity (Schieltz and Rubenstein, 2016). Low grazing intensity and the absence of fire enhance woody plant encroachment, favoring a shrub-grass vegetation pattern (Briggs et al., 2005). The absence of grazing also causes increased grass height and thickness and accumulated litter, reducing nesting habitat for some grassland birds (Askins et al., 2007). High stocking rates typically cause a downward trend in range ecological condition (Holechek et al., 1999), and sites in poorer condition support fewer grassland bird species (Askins et al., 2007). On the Canadian Prairies, a review of grazing studies reported that light (~32% use of available forage) to moderate (~43% use) grazing intensity maintained or improved range condition (Holechek et al., 1999).

Studies examining direct impacts of grazing cattle on grassland bird communities via nest trampling found few nests destroyed by cattle and few effects of grazing on grassland bird nest survival at the pasture scale, although different species had varying responses to stocking rate and number of years grazed (Pipher et al., 2016). Bleho et al. (2014) also reported that few grassland bird nests were destroyed by grazing cattle and that species-specific responses were observed, as although nest destruction generally increased with grazing pressure, nest survival was higher in more heavily grazed areas for some species. Nest destruction has been mainly attributed to predators, especially in areas adjacent to croplands (Bloom et al., 2013). Modest levels of cattle grazing have been found to increase abundance and, in some cases, species diversity of arthropod communities relative to ungrazed sites, although there were species-specific responses to grazing pressure within and between different taxa (Vankosky et al., 2017).

Land conversion and the introduction of exotic species have negatively affected biodiversity in the prairies and in North America as a whole. In the 1930s, exotic species such as crested wheatgrass (*Agropyron cristatum*) were seeded in the prairies to reduce erosion on marginal cropland and overgrazed rangelands (Agriculture Canada, 1972). Highly productive and adapted to local conditions (cold and drought tolerance, trampling resistance), it helped improve pasture-based beef production. However, crested wheatgrass out-competes native grass species and has reduced plant diversity in grasslands. Soil quality has also declined under crested wheatgrass due to increased erosion resulting from a higher proportion of bare soil, higher bulk density, fewer water stable aggregates, lower soil organic matter and N compared with native grasses (Lesica and DeLuca, 1996).

Preventing further grassland loss and maintaining or rehabilitating the integrity of remaining grasslands is vital for the conservation of grassland biodiversity (Askins et al., 2007), and appropriate grazing management plays a central role in maintaining the health of grassland flora and fauna. In the case of grassland bird communities, the variation in climatic and geographic conditions across the prairies and species-specific responses to grazing management among grassland birds makes it impossible to offer blanket prescriptions for optimal grazing management (Askins et al., 2007). Pipher et al. (2016) and Sliwinski and Koper (2015) concluded that grazing cattle at a wide range of grazing intensities is consistent with the conservation of grassland bird communities, at least in the short-term.

4. Research limitations, knowledge gaps and future priorities

Despite an extensive body of literature, many knowledge gaps exist regarding individual services and the overall ecological and social impacts of the beef sector. Foremost, perhaps, is the role of prairie beef production systems in supplying cultural services. The paucity of research on cultural services is characteristic of the ecosystem services literature, as most assessments have focussed on provisioning and regulating services which are typically simpler to define and measure. Research on the role of prairie beef production systems in providing cultural services and the development of cultural service indicators should be a priority. Future work should also focus on developing indicators of regulating services, as opposed to environmental quality, to measure actual ecological work performed under different environmental and management conditions.

The lack of such indicators is not surprising, as most reviewed studies were environmental quality rather than ecosystem service assessments. Thus, they measured the environmental impacts of beef production with little or no measurement of the social and/or economic impacts required for a full sustainability analysis, although many did acknowledge the potential consequences for the health, social and economic dimensions of human well-being. Future research in this field should link changes in service supply from beef systems to diverse dimensions of human well-being.

Also needed are more studies on long-term effects of management practices, the duration of management effects, and recovery time required to reverse adverse impacts after the adoption of BMPs, especially where ecosystem responses occur slowly, as in the regeneration of riparian areas following cattle exclusion. The timescale of ecosystem service assessment should also be extended throughout the year. For example, data on full-year effects of winter grazing and bedding areas on service supply, and in particular water, soil and air quality, are sparse. More information on the fate of N excreted on frozen feedlots and pasture soils and the consequences for air quality and GHG emissions is also needed.

Most studies were conducted in the Brown, Dark Brown and Black soil zones of southern and central Alberta, with less attention to southern Saskatchewan and the beef-producing regions of Manitoba. The heterogeneity in climate, landscapes, and practices both within and among beef operations throughout these regions makes it difficult to generalize the outcomes of ecosystem service studies from one beef system to another, indicating a need for regional ecosystem service assessment. For some services, quantifying service impacts for different western Canadian beef production systems is further hindered by a lack of regionally-specific data, such as NH_3 emission factors for grazing cattle.

Previous studies have typically focussed on a single stage of beef production in conjunction with a single ecosystem service or aspect of environmental quality. For instance, research on *E. coli* and/or antimicrobial resistant *E. coli* focused primarily on feedlot cattle, with little research on cow-calf herds. Air quality studies have mainly quantified NH_3 emissions from feedlots, with relatively few examining sources of odours or dust from the feedlot or other production stages. What is needed, therefore, are multi-factor experiments and simulation modelling on the holistic impacts on service provision of different management histories. This method, already adopted for studying farm-level GHG emissions, can point to efficient targeting of resources and management strategies to best improve service provision, without jeopardizing productivity. Where quantitative analysis is not possible, qualitative assessments incorporating a broader suite of ecosystem services and management practices can play a significant role in enhancing our understanding of the dynamics of livestock production systems and their diverse environmental and social impacts.

Extending this more holistic approach to other individual services and ecosystem service bundles could help assess how prospective practices influence trade-offs and synergies among different services (Figure 1). For instance, the deposition of manure on pasture results in lower NH_3 emissions than in feedlots, whereas grazing can increase the intensity of enteric CH_4 emissions from beef cattle. Although few studies explicitly measured the supply of multiple services, many did acknowledge the potential consequences of certain practices for other services. For instance, studies examining pathogens in cattle faeces frequently acknowledged related risks for ground and surface water contamination, even if bacterial water quality parameters were not measured in the study. Dyer et al. (2014) is one exception; they carried out a semi-quantitative assessment of the impacts of carbon footprint (CFP)-affecting practices in livestock production systems on other non-climate-related services. They reported that, in western Canada, the highest GHG emission intensity derived from animal systems due to CH_4 emissions, with the second highest emission intensity related to crop production. However, grazing animals represented only 16% of total non-CFP[5] environmental impacts, while crop production had the highest number. Such research highlights the importance of considering multiple services in assessing the sustainability of beef cattle production.

Future research should centre on: cultural services; developing indicators to measure regulating services; examining trade-offs and synergies between different services; assessing how changes in service supply affect human well-being; and understanding how changes in human well-being can in turn influence system governance and management.

5. Conclusions

Beef production systems on the Canadian Prairies are complex, dynamic social-ecological systems, where social actors and ecological elements interact to provide a range of ecosystem services and disservices. Achieving environmental, social and economic sustainability in food and agricultural production systems is emphasized in the UN's Sustainable Development Goals, which include ending hunger, achieving food security, improving nutrition, and promoting sustainable agriculture (UN, 2015). The Government of Canada's 2016-2019 Federal Sustainable Development Strategy also includes sustainable food among its 13 aspirational long-term goals (GoC, 2017). The sustainability of the industry depends on its ability to supply not just provisioning services such as beef, but also a range of regulating and cultural services.

Priorities in ecosystem services research include: the need for an interdisciplinary, systems-based approach to understand the social and ecological drivers of ecosystem service supply; the effects of spatial heterogeneity and historical legacies on service supply; how multiple services interact; and the importance of engaging stakeholders in studies of ecosystem services (Bennett, 2017). Our review provides one of the first analyses of livestock production systems that encompasses all agricultural stages of production and multiple ecosystem services. It also represents a first step in an interdisciplinary, social-ecological systems approach to ecosystem service assessment for beef production on the Canadian Prairies. Such an approach is necessary to assess the full social and ecological footprint of this industry (Hawes et al., 2016; Janzen, 2011), and to evaluate the combined effect of multiple management practices on multiple services, and trade-offs and synergies in service provision (Power, 2010). The ultimate goal in ecosystem service assessments is to identify practices which, alone or in suites, enhance

[5] Non-CFP impacts include animal welfare, disease vectors (disease transmission to other livestock, wildlife or humans), crop diversity, habitat, wildlife, topsoil (soil erosion), runoff quality, groundwater, soil organic matter.

multiple regulating and cultural services while also increasing yield and production efficiency. Such studies will also have to consider the beef system among other land uses, such as oil and gas development, mining, urbanization and transportation systems, which also affect service supply from the land.

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Appendix A. Beef management practices

The main beneficial management practices (BMPs) adopted by beef production systems in the prairies can be divided into four categories (Table A.1). These include: (1) managing inputs (nutrients, toxins, pathogens and water) to agricultural systems; (2) controlling leaching, runoff and wind, water and tillage erosion processes; (3) providing barriers and buffers to the transport of nutrients, sediments, toxins and pathogens; and (4) enhancing wild species diversity and habitat provision (AAFC, 2000; Hilliard et al., 2002). Each BMP category represents a group of more specific practices that can be implemented on a farm, some of which enhance the supply of multiple services.

Table A.1
List of BMPs that affect ecosystem service supply and specific actions for Canadian beef production systems.

(1) Input management
Nutrient management
➢ Soil and manure testing
➢ Method, timing and rate of manure and commercial fertilizer application on pasture and cropland
Integrated pest management (IPM)
➢ Information collection, threshold identification and chemical, mechanical, biological and cultural (including cattle grazing) control measures
➢ Method, timing and rate of pesticide application on pasture and cropland
Storage and handling of manure and silage, commercial fertilizers and pesticides
➢ Storage of solid cattle manure and silage to protect surface water from runoff contamination
➢ Treatment of manure from feedlots, e.g., composting, stockpiling
Livestock exclusion/restricted access watering
➢ Off-stream watering, e.g., nose pumps, pasture pipelines, pumped gravity flow reservoirs
➢ Fencing of riparian areas and surface waterbodies
➢ Designated stream and creek crossings
➢ Even distribution of off-stream drinking water sources, location and rotation of feeding and bedding sites (to prevent localised overgrazing and nutrient buildup)
Administration of pharmaceuticals
Irrigation management
(2) Process control (leachate, runoff, erosion)
Tillage regime
➢ Conservation tillage, e.g., zero tillage, minimum or reduced tillage, direct seeding, crop residues
Fallow regime
➢ Conservation fallow
Crop rotation
Strip cropping, intercropping, cover cropping
Shelterbelts/windbreaks
Lined channels and drop structures, storm water diversion (farmyard runoff)
Grazing management - stocking density, grazing regime (continuous, deferred rotational, intensive)
(3) Buffers and barriers
Vegetated buffer zones, e.g., wooded or grassed areas including silvopastures and wildlife plantings
Streambank protection
➢ Riparian buffers
➢ Controlled riparian grazing

(*continued on next page*)

Table A.1 (*continued*)

Wetlands
➢ Natural wetlands
➢ Constructed wetlands
Grassed waterways
Holding/retention ponds and catch basins (feedlots)
(4) Wild species diversity and habitat provision
Native plant establishment on pastures
Conversion of marginal or unproductive cropland to perennial or permanent cover

Source: modified from AAFC (2000), AAFRD (2004a, 2004b, 2006), AARD (2010), GoA (2014), GoS (2016), Hilliard et al. (2002), MacKay (2010), Stuart et al. (2010).

Appendix B. Web of Science[6], Scopus[7] and Google Scholar search terms

Search term combinations:

- 'ecosystem service' OR 'ecological service' OR 'environmental service' AND 'Canada' AND 'beef' OR 'agriculture' OR 'prairies' OR 'rangelands' OR 'grasslands'
- 'life cycle assessment' AND 'Canada' AND 'beef' OR 'cattle' OR 'agriculture'
- 'nutrient cycling' OR 'nitrogen cycling' OR 'phosphorous cycling' OR 'carbon cycling' OR 'water cycling' OR 'primary productivity' AND 'Canada' AND 'beef' OR 'agriculture' OR 'prairies' OR 'rangelands' OR 'grasslands' OR 'feedlot' OR 'barley' OR 'oat' OR 'corn'
- 'water consumption' OR 'water demand' OR 'water use' OR 'irrigation' AND 'Canada' AND 'agriculture' OR 'crops' OR 'beef' OR 'livestock' OR 'cattle' OR 'rangeland' OR 'grassland' OR 'pasture' OR 'barley' OR 'oat' OR 'corn' OR 'forage'
- 'water quality' OR 'water pollution' OR 'eutrophication' AND 'Canada' AND 'agriculture' OR 'livestock' OR 'cattle' OR 'fertilizer' OR 'herbicide' OR 'pesticide' OR 'manure'
- 'air quality' OR 'air pollution' OR 'atmospheric pollution' AND 'Canada' AND 'agriculture' OR 'livestock' OR 'cattle' OR 'fertilizer' OR 'manure' OR 'dust' OR 'ammonia'
- 'pollution control' AND 'Canada' AND 'agriculture'
- 'soil erosion' OR 'erosion control' OR 'erosion regulation' AND 'Canada' AND 'agriculture' OR 'livestock' OR 'cattle'
- 'soil quality' OR 'soil nitrogen' OR 'soil phosphorous' AND 'Canada' AND 'agriculture' OR 'livestock' OR 'cattle'
- 'soil carbon' OR 'soil organic matter' OR 'soil organic carbon' OR 'carbon storage' OR 'carbon sequestration' OR 'climate regulation' OR 'greenhouse gas' AND 'Canada' AND 'agriculture' OR 'livestock' OR 'cattle' OR 'beef'
- 'hazard regulation' OR 'flood regulation' OR 'flood control' OR 'flooding' AND 'Canada' AND 'agriculture'
- 'disease' AND 'Canada' AND 'livestock' OR 'cattle'[8]
- 'cattle' AND 'Canada' AND 'coli' OR 'salmonella' OR 'anthrax' OR 'BSE' OR 'bovine spongiform encephalopathy' OR 'Q fever' OR 'cysticercosis' OR 'campylobacter' OR 'clostridium' OR 'cryptosporidium' OR 'giardia' OR 'listeria' OR 'salmonella' OR 'shigella'
- 'tourism' OR 'ecotourism' AND 'Canada' AND 'agriculture' OR 'farm'
- 'agri-tourism' AND 'Canada'
- 'cultural service' OR 'cultural heritage' AND 'Canada' AND 'agriculture' OR 'farm' OR 'beef'

Appendix C. Definition of scores for Table 1 and Table D.1

Beef influence on service supply:
Large positive - a long-term potential enhancement of ecological and/or social well-being via the sustained supply of this service from the system;
Moderate positive - a moderately positive impact on service supply that enhances ecological and/or social well-being;
Slight positive - a small and/or occasional positive impact on service supply;
No change;
Slight negative - a small and/or occasional negative impact on service supply;
Moderate negative - a moderately negative impact on service supply that is not sustainable in the long-term and will eventually lead to declines in ecological and/or social well-being;
Large negative - a decline in the supply of a service that is not sustainable in the medium- to long-term and cannot continue without lasting irreparable damage and significant declines in ecological and/or social well-being.
Confidence in data:
High - the data are direct measurements of the parameter under examination and are associated with a low level of uncertainty;
Medium - the data are direct measurements of the parameter under consideration but are associated with some uncertainty, e.g., confidence in

[6] Databases included: WoS Core Collection, BIOSIS Citation Index, Current Contents Connect, Data Citation Index, Derwent Innovations Index, KCI Korean Journal Database, MEDLINE, Russian Science Citation Index, SciELO Citation Index, Zoological Record

[7] All subject areas: life sciences, health sciences, physical sciences and social sciences and humanities

[8] Includes bovine zoonoses listed on the reportable diseases list of the Canadian Food Inspection Agency, and the provincially reportable and notifiable diseases lists for cattle in AB (AAF, 2017), SK (GoS, 2017) and MB (GoM, 2017). These criteria identified anthrax, bovine spongiform encephalopathy (BSE), Q fever and cysticercosis (CFIA, 2016). Common reported food and waterborne pathogens and parasites in Canada that can originate from manure-contaminated water include *Campylobacter* spp., *Clostridium* spp., *Cryptosporidium* spp., *Giardia* spp., *Listeria* spp., *Salmonella* spp. and Shiga toxin-producing *Escherichia coli* (Butler-Jones, 2013; Hilliard et al., 2002).

estimates of water consumption for forage and feed production is medium due partly to uncertainties associated with the import and export of water embedded in feed and forage crops and beef cattle products imported to and exported from the prairies; confidence in the impact of beef production on water quality is medium due to difficulties in distinguishing the impacts of beef production from those of other drivers of change on water quality parameters, particularly at the watershed scale;

Low - the available data is sparse and/or is not a direct measurement of the parameter under examination, e.g., confidence in estimates of recreation and tourism are low as the underlying literature provides only general information on rural tourism and beef farms rather than specific measures of the service such as number of visitor days.

Responsiveness to management:

High - currently available management practices can cause significant changes in service supply, e.g., restricting cattle access to surface water bodies, feedlot catch basins and appropriate rates and methods of fertilizer application can significantly improve water quality;

Medium - currently available management practices can have a moderate impact on service supply, e.g., improved management practices can achieve moderate gains in the yield and quality of beef cattle products;

Low - currently available management practices have little impact on service supply, e.g., water consumption on pasture and in the feedlot is mainly by livestock, where the quantity of water is only marginally influenced by management; biodiversity and habitat quality in feedlots is generally low and unlikely to be influenced by management practices.

Opportunity to improve:

High - there is a high potential for significant further improvements in service supply through further research that may shed light on the relationships between management regimes, social and ecological structures and processes and service flows, e.g., on pasture, further research on the impacts of grazing regimes and stocking densities on different pasture types may facilitate the development of pasture management strategies that enhance grassland biodiversity and habitat quality; given the relative paucity of information on recreation and tourism on beef operations, further research may provide insight into how recreation and tourism opportunities on beef ranches could be developed;

Medium - there is some potential to gain further insight into how to improve service supply via the adoption of certain management practices, although this may be limited by extensive research that has already been conducted in this field or because the services themselves are somewhat unresponsive to management;

Low - there is little opportunity for further improvement in service supply, e.g., further research on the impacts of pasturing cattle on air quality (NH_3, unpleasant odours, PM) is unlikely to lead to increases in the supply of this service as pasturing cattle has a relatively low overall impact on air quality; although considerable increases in live and carcass weight of Canadian beef cattle have been achieved since the 1950s, there is limited potential for further increases.

Appendix D. Table 1 scores for ecosystem services and individual indicators

Table D.1
Summary of the influence of the agricultural stages of beef production on ecosystem services in the prairie provinces; level of confidence in the existing data on the influence of beef production on service supply; the responsiveness of different services to management practices; and the opportunity to improve service supply from these systems via further research. This table includes the overall scores for each service and the scores for individual indicators.

Ecosystem service	Beef influence on service supply			Confidence in data on service supply			Responsiveness to management			Opportunity to improve			Relevant text section
	P	F	C	P	F	C	P	F	C	P	F	C	
Provisioning services													
Food production	+ Moderate	+ Large	/	H	H	/	M	M	/	L	L	/	3.2.1
Meat quality	+ Moderate	+ Large	/	H	H	/	M	M	/	L	L	/	3.2.1
Meat quantity	+ Moderate	+ Large	/	H	H	/	H	H	/	L	L	/	3.2.1
Non-food goods production	+ Moderate	+ Large	/	H	H	/	M	M	/	L	L	/	3.2.1
Non-meat goods quality	+ Moderate	+ Large	/	H	H	/	M	M	/	L	L	/	3.2.1
Non-meat goods quantity	+ Moderate	+ Large	/	H	H	/	M	M	/	L	L	/	3.2.1
Water supply[1]	− Slight	− Slight	− Large	H	H	M	L	L	H	L	L	M	3.2.2
Regulating services													
Water quality regulation	− Slight	− Moderate	− Moderate	M	M	M	H	H	H	M	M	M	3.2.3
Pathogens	− Slight	− Moderate	− Moderate	M	H	M	H	H	H	M	H	M	3.2.3
Sediment	− Slight	− Slight	− Moderate	M	M	M	H	H	H	L	L	M	3.2.3
Nutrients (N, P, K)	− Slight	− Moderate	− Moderate	M	H	H	H	H	H	M	M	M	3.2.3
Trace elements	/	− Moderate	− Moderate	/	M	M	/	H	H	/	M	M	3.2.3
Pesticides	/	/	− Moderate	/	/	M	/	/	H	/	/	M	3.2.3
Pharmaceuticals	− Slight	− Moderate	/	H	H	/	H	H	/	L	M	/	3.2.3
Air quality regulation	+ Moderate	− Moderate	− Slight	H	H	H	L	L	H	L	M	H	3.2.4
NH_3	− Slight	− Moderate	− Slight	H	H	H	L	L	H	L	H	H	3.2.4
Unpleasant odours	+ Moderate	− Moderate	− Slight	H	H	L	L	L	L	L	M	L	3.2.4
Dust	+ Moderate	− Moderate	− Slight	H	H	H	H	L	L	L	M	L	3.2.4
Pesticides	/	/	− Slight	/	/	M	/	/	H	/	/	M	3.2.4
Pharmaceuticals	+ Moderate	− Slight	− Slight	L	L	M	H	L	M	L	L	M	3.2.4
Disease regulation	− Slight	− Moderate	/	M	H	/	H	H	/	M	H	/	3.2.5
E. coli	− Slight	− Moderate	/	H	H	/	H	H	/	M	H	/	3.2.5
Salmonella spp.	− Slight	− Moderate	/	M	H	/	H	H	/	M	H	/	3.2.5
Campylobacter spp.	− Slight	− Moderate	/	M	H	/	H	H	/	M	H	/	3.2.5
Giardia spp.	− Slight	− Moderate	/	M	H	/	H	H	/	M	H	/	3.2.5
Cryptosporidium spp.	− Slight	− Moderate	/	M	H	/	H	H	/	M	H	/	3.2.5
Soil quality regulation	+ Slight	− Moderate	− Moderate	H	H	H	H	H	H	M	M	M	3.2.6
Erosion risk	− Slight	− Slight	− Moderate	H	H	H	H	H	H	L	L	M	3.2.6
Nutrients (N, P, K)	+ Moderate	− Moderate	− Moderate	H	H	H	H	H	H	L	M	M	3.2.6
Trace elements	/	− Moderate	− Moderate	/	H	H	/	H	H	/	M	M	3.2.6
Pesticides	/	/	− Moderate	/	/	H	/	/	H	/	/	M	3.2.6
Pharmaceuticals	− Slight	− Moderate	− Moderate	H	H	H	H	H	H	L	M	M	3.2.6
Climate regulation	− Moderate	− Slight	− Slight	H	H	H	L	L	L	H	H	M	3.2.7
CH_4	− Large	− Slight	/	H	H	/	L	M	/	H	H	/	3.2.7
N_2O	− Slight	− Slight	− Moderate	M	M	M	M	M	H	H	H	M	3.2.7
CO_2 (energy)	− Slight	− Slight	− Moderate	H	H	H	L	L	L	L	L	L	3.2.7
CO_2 (soil)	+ Moderate	/	− Slight	L	/	L	H	/	H	H	/	H	3.2.7
Cultural services													
Cultural heritage	+ Large	/	/	L	/	/	L	/	/	M	/	/	3.2.8
Recreation and tourism	+ Slight	/	/	L	/	/	H	/	/	H	/	/	3.2.8
Biodiversity and habitat													
Biodiversity	+ Large	− Large	− Slight	M	H	M	H	L	M	H	L	H	3.2.9
Habitat maintenance	+ Large	− Large	− Slight	M	H	M	H	L	M	H	L	H	3.2.9

Legend

Beef influence
Positive: Large, Moderate, Slight
No change
Negative: Slight, Moderate, Large

/ Not relevant

Confidence in data/ Resp. to management/ Opportunity to improve
L Low
M Medium
H High

P = pasture; F = feedlot; C = cropland. [1]Water supply = blue water (surface and ground water) consumption. See Appendix C for score definitions.

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